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Multi-product EVSM simulation

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Abstract

Value stream mapping (VSM) has been a widely used method aiming at the elimination of inefficiencies in manufacturing systems. During the last few years VSM was extended towards the consideration of energy demands of processes and supporting services (EVSM), material use, multi-product perspective, as well as the impact of different product characteristics. However, since VSM is a static method, it is not possible to completely analyze the dynamic interrelations between jobs. This paper proposes a simulation tool which allows the analysis of multiple value streams for different products regarding lead times, as well as non-value adding times and energy demands.

Keywords: Value stream mapping; Simulation; Multi-product; Energy efficiency

1. Introduction

Products are typically embodied through a defined sequence of value adding manufacturing processes supported by auxiliary processes (e.g. transportation). Within this process chain – typically referred to as value stream – input raw materials are transformed from an initial state to a predefined final state while demanding personnel, auxiliary materials and energy (e.g. [1, 2]). Traditionally, costs, time and quality are considered as main target dimensions for value streams. Within the last few years, also sustainability oriented objectives like energy demand or related emissions have strongly gained relevance.

For systematically analyzing and improving process chains, value stream mapping (VSM) is an established method [3]. VSM was also extended with aspects like energy demands (energy VSM/EVSM) in the last years (e.g. [4, 5]). However, one of the general shortcomings of (E)VSM is the static representation neglecting dynamic interdependencies within value streams (e.g. process waiting times through failures on upstream processes). Even more, (E)VSM is limited for application in multi-product environments since existing interactions of different value streams (e.g. bottleneck situations on shared machines) cannot be depicted.

Against this background, this paper presents a simulation based EVSM approach for simultaneously considering multiple product value streams in factories. Therewith, system behavior can be predicted more realistically and systematic improvement is being fostered.

2. Background

2.1. Value stream mapping – principles and shortcomings

The traditional value stream mapping (VSM) methodology provides a simplified and static representation of a product's value stream and all related activities, highlighting the value adding and non-value adding steps [3]. In the first step of VSM, a product or a product family is selected as an object for analysis. In the second step, a current state value stream map is created including all processes, buffers, and information flows required for the fabrication of the product under survey. For each process, the current state parameters such as processing time, lead time, level of inventory, and availability are determined on the factory shop floor and added to the value stream map. Based on this second step, hot spots for improvement can be identified and specific measures can be developed. In the third step, a future state map is

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created showing the value stream including improvement measures. The application of VSM can be paper-based, it uses standardized and well-known figures and icons for representation of the value stream map, it is easy to learn, and the results are easy to understand even without having expert knowledge. These advantages make VSM an important methodology for production planners.

However, there are some limitations to the traditional VSM methodology. Due to the simplifying nature of VSM, processes are modeled with constant values (e.g. for process times) based on average values or one-time measurements [6]. Additionally, a value stream map has to be created for each product or product family. These assumptions neglect the dynamic behavior of processes and machines as well as the facts that different product properties may require different processing times, that batch size does not necessarily have a linear correlation to the processing time, that different jobs require different routings, and that a job may affect other jobs by blocking of resources resulting in fluctuating waiting times. Furthermore, the snap-shot perspective of one-time measurements comprises the risk of not capturing the actual average situation on the shop floor [7]. As a consequence, traditional VSM is suitable for the analysis of mass productions but not for a manufacturing system handling a product spectrum with high variety [8]. In addition to these shortcomings, VSM in its original form only allows to consider traditional manufacturing objectives such as lead time and non-value adding time shares. Not included in VSM are ecological objectives and key performance indicators (KPI). These shortcomings and drawbacks have led to various extensions to VSM.

2.2. Energy value stream mapping

In order to include energy demands of processes into VSM, the methodology has been extended to the energy value stream mapping (EVSM). In the initial EVSM approach, the direct energy demands of processes were included for the energy carrier electricity, compressed air and gas. These demands are used to calculate the energy intensity (EI) of each process in order to identify the main energy consumers [4]. This approach neglects the dynamic behavior and different states of production machines (e.g. ramp-up, idle, processing) as well as indirect energy demands from auxiliary equipment (e.g. compressed air generation) and technical building services (e.g. air suction and heating). However, the energy demands from non-productive states of machines and indirect consumers can cause a significant share of the total energy demand [9, 10]. To address these shortcomings, Bogdanski et al. and Posselt et al. have proposed extended EVSM approaches considering different machine states and allocation mechanisms for indirect energy demands [5; 11]. These extensions allow evaluating the ecological and economic impacts of energy consumption in a holistic manner.

2.3. EVSM and multi-product perspective

Product characteristics can have a significant effect on the value stream of a product [5]. However, traditional VSM alone is not capable of representing different product types within one value stream map simultaneously. Consequently it is not possible to use VSM for identifying the influences of product characteristics on process state parameters and manufacturing objectives. Gained knowledge about these influences would be relevant for product designer in order to achieve a good manufacturability. Furthermore, neglected are the dynamic interdependencies between jobs of different product types. This, however, is relevant since often same production resources (e.g. CNC machines) are used to process different product types.

Schönemann et al. suggested integrating product characteristics into value stream modeling with the goal to use EVSM for analyzing the impact of product characteristics on manufacturing. Their developed concept allows evaluating the impact of specific product characteristics with respect to lead time and energy consumption of a job [12]. However, their approach is static and does not allow considering the interdependencies between different jobs of different product types.

2.4. Simulation and VSM

As a solution to overcome the static character and the snap-shot view of VSM, proposed in various publications is the combination of VSM and simulation [7; 13–16]. Simulation is a widely used methodology in industry and research which aims at analyzing the behavior of a real world system over time. Simulation uses a simplified model of a real system to perform experiments and to acquire results which are transferable to reality. Further background information about simulation can be found for example in [17]. Comprehensive reviews of simulation approaches and applications in the context of manufacturing system are provided for example in [18, 19].

Gurumurthy and Kodali provide a literature review about the different VSM simulation application [14]. In all mentioned approaches, simulation models were developed additionally to the creation of value stream maps. That means that drawbacks of simulation such as time effort and required expert knowledge are not eliminated. Furthermore, these published simulation applications were modeled only for specific cases implying a high degree of complexity and no flexibility regarding the modification for other manufacturing systems. A configurable simulation approach for the analysis of material flows and energy demand profiles is presented in [20]. It allows the user friendly definition of a process chain but is limited to a fix number of work stations and does not allow a multi-product analysis. As a consequence, still required is a method that allows the easy definition, analysis and interpretation of value streams including the dynamic behavior within manufacturing systems.

3. MEVSM simulation concept

The proposed method combines the benefits of extended EVSM with an easy-to-handle simulation tool in order to realize a Multi-product EVSM (MEVSM) simulation approach. To cover manifold value streams and manufacturing process chains, the approach is designed to be user-friendly and individually configurable. It further enables simulative assessments regardless of the user's knowledge about simulation. This helps in revealing dynamic effects of multiple value streams for different products and jobs during a given period of time such as longer lead times, different energy demands as well as scheduling potentials. Due to the seamless integration of the modularized simulation tool in the approach, users do not have to spend vast amounts of time to build up individualized simulations themselves and yet use its advantages. Thus, the approach can be regarded as a synergetic integration of simulation and static EVSM methods to overcome disadvantages of both methods while profiting from their advantages. To ensure an easy comprehensibility, appropriate key figures and means for visualization such as the value stream mapping representation are used to facilitate decision support. Furthermore it is crucial to understand that developed was not a specific calculation and simulation tool but a generic and adaptable approach.

3.1. MEVSM workflow

The conceptual workflow of the proposed approach can be subdivided into two different perspectives: the user perspective which represents the front end and the data perspective indicating the back end. Figure 1 shows both perspectives and three work steps that are linked with each other by data flows. In the first step, the user defines specific value streams of different product types based on measured production data. In the second step, the (energy) value streams are imported to a simulation tool which determines the dynamic flow of jobs through the virtual manufacturing system. In the third step, the simulation results are evaluated regarding various key performance indicators and objectives.

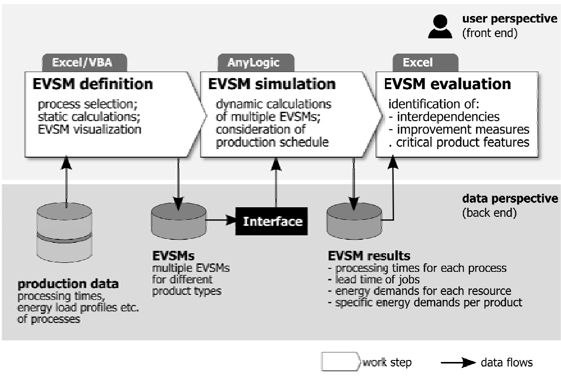

Fig. 1. Workflow of MEVSM concept

3.2. EVSM definition and calculation

In order to define one or multiple EVSMs it is inevitable to initially gather different production, process and energy data. The data source in that regard can vary from automated data monitoring systems to manually recorded machine data such as load profiles or state based power demands of machines. All information is stored in a structured data back end.

The definition of respective EVSMs, the selection of the available data about processes and related machines is done by the user via a tool based on Excel®. This tool allows the user to configure the relevant EVSM(s) through different user forms and provides the option to calculate and visualize static EVSMs. This includes key figures such as lead time and energy demand per product, state-based energy demand per machine per day as well as further conventional key figures such as bottleneck machines, cycle times, production flow rate etc. Figure 2 shows the main elements of the tool for static EVSM definition and calculation.

In addition to separate analyses of single EVSMs and its respective calculations and visualization, the user can also define multiple EVSMs for different products and various jobs that are supposed to run through the same manufacturing system. Each EVSM can be parameterized according to the characteristic of each product typ. For example, different product types have different sequence of processes and different process parameters. Figure 3 illustrates the material flow of jobs for different product types and the influences of product specific process sequences on processes.

The interferences of different jobs which are using the same resources could for example cause an increase in lead time (LT) or energy demand (ED) of a job due to longer idle times of involved machines.

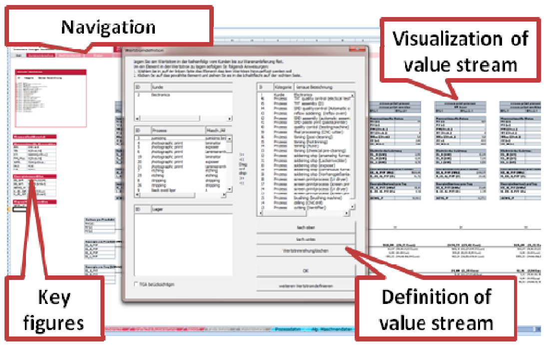

Fig. 2. Calculated EVSM of a specific job

3.3. MEVSM simulation

The different EVSMs can be saved to or loaded from an EVSM interface. It contains all relevant EVSM data and connects the first with the second work step from a data perspective. This closes the gap between the static EVSM definitions in Excel® with the EVSM simulation executed in AnyLogic®.

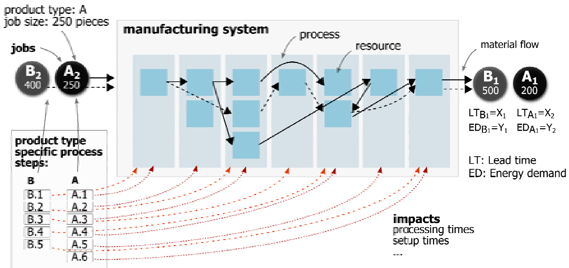

Fig. 3. Multiple EVSMs with different product types and jobs in manufacturing system

The simulation of multiple production jobs is then realized following a discrete-event and agent-based approach. Single product jobs are modeled as agents who move through a given manufacturing system according the required work packages.

Each product or job agent is an individual instance of its class being able to provide information about the required processing to work stations and to store information about the progress of manufacturing or the embodied energy. The work stations are also modeled as individual agents. Figure 4 shows the three main elements of a work station in the MEVSM simulation.

The first element illustrates the representation of a work station on the manufacturing system level including a few key figures. The second element indicates the different operational states ranging from off to ramp up, idle, and processing state. Each state is triggered by different transitions such as messages, timeouts, conditions or (product) agent arrivals depending on the state and transition of the respective product agent. The combination between the work station agents and the product agents is shown in the third element, the product entity flow. This element is based on discrete event simulation and therefore only induces and triggers events at discrete time steps. Products waiting before processing and actual product processing represent for example such events.

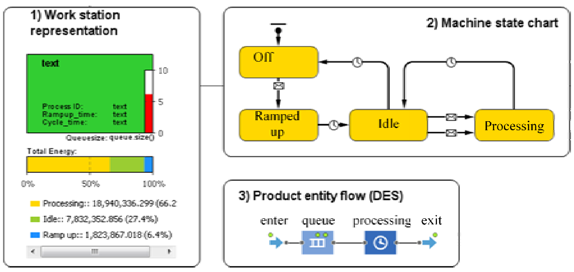

Fig. 4. Work station agent in MEVSM simulation

For each product type, the simulation provides multiple simulated EVSMs according to the production schedule. These EVSMs provide information about the used work stations and resources, the processing and waiting times for each process, the cumulated direct ramp up, idle and processing energy demand as well as the lead time of all simulated jobs. The resulting numerical values for lead times and energy demand are influenced by the offered jobs which were processed in the manufacturing system at the same time. That means that the value streams of the same product type can differ from each other. In addition to that, dynamic energy load profiles of machines and work stations can be drawn automatically.

The simulation process and its dynamic calculations of the respective EVSMs are further visualized by an arranged manufacturing system that adapts according to the amount of work stations involved in all EVSMs. The alignment of the work stations is based on a coordinate system with an x- and y-axis, respectively that can be configured by the user in Excel®. This option further contains the potential to specify distances and transport times between work stations to consider additional key figures. Figure 5 shows four different work stations as a section of a manufacturing system including two different product jobs indicated as circles inside two of the work station boxes. The four work stations are in different states respectively as highlighted by the differing colors and the status note on top of every work station. General information about each process is provided inside each work station box such as the process identification number as well as ramp up and cycle times. The energy demand per state is further shown below every work station by a bar chart.

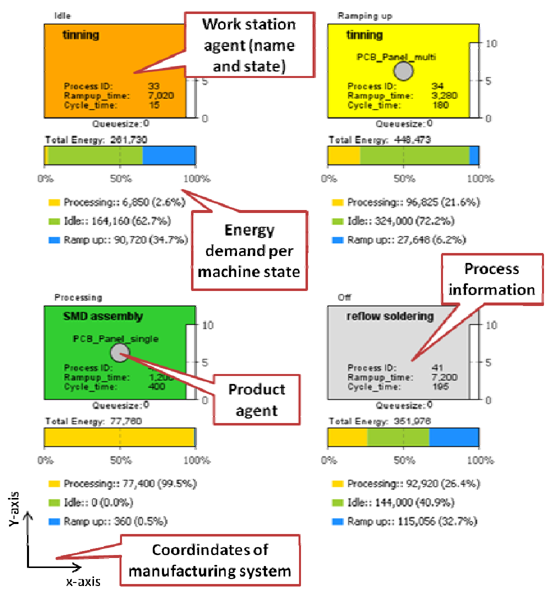

Fig. 5. Manufacturing system representation in MESVM simulation

3.4. MEVSM evaluation

Subsequent to simulating multiple EVSMs in a manufacturing system, the third work step deals with an evaluation of the EVSM results. The evaluation is crucial to identify measures of improvement for current as well as future production planning and scheduling. To achieve that, each job provides information about the prorated work station energy demand per total embodied job energy. This information gives a good starting point to see which work station has the highest energy related influence on the product job.

As a next step, the simulated EVSM process notation per product job gives an advice on the share of value adding and non-value adding time per work station as well as information about the total lead time and total energy demand per product piece, as shown in Figure 6.

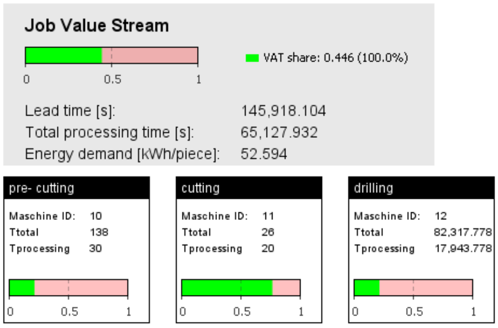

Fig. 6. Section of exemplary dynamically drawn product job value stream

The shown dynamically drawn product job value stream also contains information about the respective work stations such as machine identification and processing time. The results may vary per product job depending on the inherent independencies between the different product jobs and production schedules. To reveal such interdependencies the lead time and total energy demand of multiple product jobs with varying job sizes can be compared to derive recommendations for optimal multi-product job schedules and strategies.

4. Application on manufacturing of electronic components

The developed concept of MEVSM simulation was applied to the manufacturing of printed circuit boards (PCB). This case was chosen since a sound amount of data was available from former VSM studies. Furthermore, the manufacturing of PCB requires many different chemical and mechanical processes with automated and manual tasks as well as various handling operations. PCBs can be differentiated regarding product characteristics such as materials, number of conductive layers and used sides (single layer, double sided single layer, multilayer). All types of PCB require almost the same processes and resource but multilayer PCB require more and specialized processes compared to single layer boards.

To analyze the effects of multi-product job schedules of PCBs being manufactured on the same manufacturing system, three scenarios for evaluation are defined as follows:

- Scenario (S1): One product type (single sided PCB), five jobs
- Scenario (S2): Two product types (single and double sided PCB), ten jobs with five jobs of single sided PCB and five jobs of double sided PCB
- Scenario (S3): Three product types (single and double sided as well as multilayer PCB), ten jobs with five single sided PCB jobs, 2 jobs of double sided PCB and three jobs of multilayer PCB.

For all three scenarios, a total of 50 single sided PCB is produced within five jobs. All three scenarios were tested with uniform and different job sizes, respectively. The variation in job size was conducted to further examine dynamic variations that can neither be identified nor quantified with solely static calculations of EVSM. For S2 and S3, the total quantity was increased to 100 PCB while keeping the quantity of single sided PCBs constant at 50.

At first, the influence of job sizes on the lead time as well as the job idle related energy demand is examined for S1. This case was chosen to compare the results that come from static calculations with a uniform job size and the variation in job size of the same product type resulting from the simulation. The results of this comparison are shown in Figure 7.

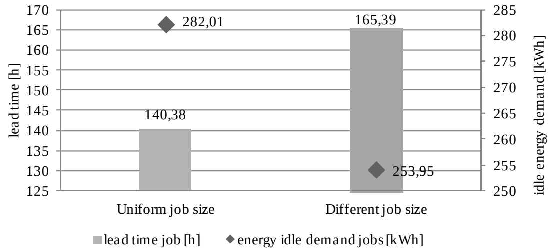

Fig. 7. Lead time and idle energy demand for uniform and different job size

The results show that a uniform job size of 10 in five different jobs led to a shorter lead time by 18% than a varied job size with the same overall quantity of 50. However, the idle energy demand of the varied job size is 11% lower than in the uniform case. This difference can be explained by the implemented control mechanisms and logic of the work stations and product job arrival rate. Depending on the utilization of the respective work stations, some work stations switch to an off state after a certain period of time. To be ready for machining again such work station have to ramp up which takes longer than to switch between the idle and processing state. Therefore, the overall lead time of the varied job size takes longer than the uniform job size. However, since some work stations are switched off for some time the idle related energy demand, as the prevalent energy demand in this comparison, decreases for the varied job size as well. This is because the off and ramp up state of the work stations have a lower energy demand than the work station's idle state. These differences in lead time and idle energy demand can only be identified through the comparison of a static and simulation based calculation, but not with a static approach alone. Thus, EVSM simulations further provide the opportunity to assess dynamic influences of multi-product schedules in terms of time and energy demand. The variation of differences of multi-product schedules is left to the user's judgment and can be assessed with this approach beyond static calculations.

Another simulation study compared the lead times of all three scenarios (S1-S3) for both job size variations, as shown in Figure 8. The results indicate that static calculations (I) only provide the results for the first bar of S1. All other results are taking dynamic influences (II) into account and can only

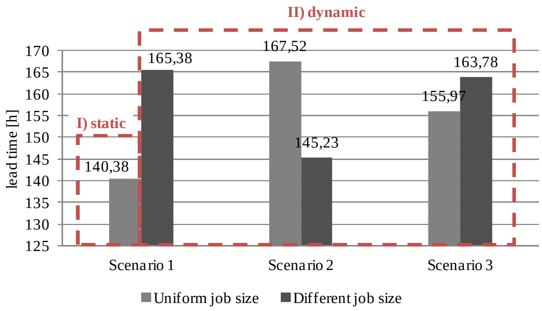

Fig. 8. Comparison of lead time for all three scenarios

be achieved through simulative assessments. The results show that a uniform job size is not necessarily the fastest way to produce a certain multi-product job schedule. Depending on the involved machines and their availability, a multi-product schedule with a varied job size might be better in terms of lead time due to more variation and fewer queuing of products. The comparison of the scenarios also shows a variation in lead time for jobs with different job sizes such as between S1 and S2 by 14%. These differences can only be identified through simulative assessment of job schedules which helps to extent the static perspective by revealing a more realistic insight into the manufacturing system behavior. Simulation enhances the information value of VSM analyses.

5. Conclusion and outlook

The presented concept for MEVSM evaluation combined with the developed simulation tool enable to avoid the static character of traditional VSM applications. It allows including multiple product types within one analysis and considering the dynamic interactions between different jobs during a given time period. This helps to improve VSM results in order to achieve more realistic results which are in line with what actually happens on the factory shop floor. Sticking to the conventional VSM logic ensures that production planners and managers are still familiar with the VSM definition and result interpretation. Special attention has been paid to the configurability and ease-of-use of the method and the tool. As a result, sophisticated simulation knowledge is not required and the EVSM definition tool based on Excel® allows representing any VSM or manufacturing system which can be transformed into a simulation application.

The exemplary application to a manufacturing system for PCB has shown that the method can provide insight in the system behavior, determine key performance indicators, and point out trade-offs between objectives. The discussed results revealed that the lead time can be influenced by different control and shut-down settings of machines which in turn may results in different idle energy demands.

The developed tool enables production planners to analyze these effects of different controls strategies for their manufacturing system under survey.

Ongoing research focuses on the implementation of pre-defined machine control strategies, standardized reports, as well as algorithms for the optimization of material flow routes and job scheduling. The goal is to further simplify the analysis of different production strategies and to enable the optimization (for the entire system or for each job) regarding different economic or ecological objectives such as “processing with shortest lead time” or “processing with lowest total energy demand”.

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